REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-29-2007

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
06/01/06-11/30/06

4. TITLE AND SUBTITLE
Scheduling Under Uncertainty: An Analysis of an Air Force Application

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-06-1-0421

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Adele Howe and L. Darrell Whitley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Colorado State University
Fort Collins, CO 80526

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of the Air Force
Air Force Office of Scientific Research (AFOSR)
875 N. Randolph St.
Arlington, VA
22203-1768 Dr Todd Combs/NM

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited

AFRL-SR-AR-TR-07-0089

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We investigated a new scheduling application under uncertainty: the Eglin AFB phased array radar tracks thousands of objects in space. Because of uncertainty associated with an object's location and radar cross-section, as well as the inherent power limits and weather, scheduling must trade-off maximizing the probability of detection against maximizing the total number of objects scheduled for observation; the system must also dynamically reschedule missed observations and incorporate new requests.

The problem of scheduling under uncertainty, and what scheduling methods are robust under uncertainty, is not well understood. We developed and tested algorithms that can handle uncertainty during scheduling. We identified key factors that impact performance and algorithm characteristics that address it.

15. SUBJECT TERMS
optimization, scheduling

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Final Report for AFOSR #FA9550-06-1-0421
Scheduling Under Uncertainty: An Analysis of an Air Force Application
June 1, 2006 to November 30, 2006

Adele Howe L. Darrell Whitley
Computer Science Department
Colorado State University
Fort Collins, CO 80524
email: {howe,whitley}@cs.colostate.edu

January 29, 2007

Abstract

We investigated a new scheduling application under uncertainty: the Eglin AFB phased array radar tracks thousands of objects in space. Because of uncertainty associated with an object's location and radar cross-section, as well as the inherent power limits and weather, scheduling must trade-off maximizing the probability of detection against maximizing the total number of objects scheduled for observation. The scheduler must also dynamically reschedule missed observations and incorporate new requests.

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Contents

1 Project Objectives

Uncertainty figures prominently in many applications that are critical to the Air Force. Most scheduling methods assume that *perfect information* is available, when in reality, most problems are characterized by varying degrees of uncertainty found in the real world. Our long term goal is to develop new algorithms for scheduling *given inaccurate information.* Until recently, few solutions have been proposed and tested for scheduling under uncertainty. In the six months of this project, we had two primary objectives:

1. Analyzing a new Air Force relevant application that requires scheduling under uncertainty: Eglin phased array radar tracking. This application is oversubscribed (more tasks are requested than the resources can always accommodate), requires optimizing about uncertainty (scheduled tasks often do not achieve their goals) and is best served by an agile, combination on-line and off-line method that can reschedule when necessary (due to task failure or to unexpected task arrival). To expedite our studies, we developed two problem generators and a simulator of the application. One problem generator followed standard practice for benchmark problem generation in scheduling; the other was application consistent and incorporated real orbital object data and constraints. The software will also allow other researchers access to a real world application of interest to the Air Force.

2. We evaluated two categories of algorithms for solving this application. On-peak algorithms follow the current practice and place all tasks at the optimal point in their scheduling windows for maximizing the probability of successful task completion. Off-peak algorithms consider alternative placement of tasks and so may sacrifice expected success for fitting more tasks in. We examined trade-offs in expected success and utilization and assessed the importance of algorithm design decisions.

2 Accomplishments/New Findings

The Space Surveillance Network (SSN) is a collection of optical and radar sensor sites situated around the globe. The mission of the SSN is to maintain a catalog of objects orbiting the earth (functional artificial satellites as well as orbiting debris). This catalog contains information about an object's orbital trajectory that is useful for facilitating observation and contact, preventing potential collisions during space missions, and predicting when specific orbits will decay.

In this research, we focus on "mission scheduling" for a particular constituent of the SSN: the AN-FPS/85 phased array radar at Eglin Air Force Base in Florida, USA (we refer to the application as "Spacetrack") [1]. At schedule generation time, radar operators at Eglin receive a list of requests for making observations on particular objects, along with a tasking *priority.* High priority tasks must be tracked while lower priority tasks are of less importance.

[1]We thank Patrick O'Kane and Richard Frank at ITT Industries for introducing us to this problem and providing us with considerable information about it.

The application is uncertain. The location of the object is not accurately known; thus, an attempt to track may not be searching the needed portion of the sky. The signal-to-noise ratio varies considerably with the objects (their distance, position during their pass, radar cross-section, etc.) and the power expenditure of the device. Thus, a scheduled task may not actually succeed and may need to be re-scheduled for a later pass.

It is important to look at real world applications for two reasons. First, the size and complexity of real world applications is usually much greater than what is observed in toy benchmark problems such as job shop scheduling. For Spacetrack, it is normal to schedule 2000 to 4000 tasks per day. Second, real world applications involve additional unexpected issues than never arise in artificial domains. For example, Spacetrack requires some form of probabilistic modeling in the presence of incomplete or imperfect information to solve for the expected value of a proposed schedule.

We have developed a high fidelity model of the Eglin tracking system in which energy and time must be allocated to tasks in order to take measurements on objects in orbit around the earth. We have also obtained a large amount of real data; we have data on approximately 6000 objects which is roughly half of all the significant objects (junk and satellites) known to be in orbit. Tracking tasks have a nonzero probability of failure, but their *expected contribution* to the final objective value of a schedule can be modeled probabilistically as a function of schedule decision variables. This result comes from the fact that the probability of successful detection is related directly to the expected position of an object in the radar's frame of reference when tracking is scheduled to occur.

The amount of power required and the probability of observing and tracking an object is affected by the object's range and the object's position and orientation. An object is said to be "on-peak" when the probability of detecting the object is greatest; currently all scheduling is done "on-peak." However, restricting observations to only "on-peak" may limit the total number of observations possible. The goal in this case is to maximize the total number of successful tracks in a given time period (or to minimize the time needed to track a given set of objects). Also, some objects have higher priorities than others, and some objects must be tracked more frequently than others.

On-peak is optimal when the energy constraints are absent. However, when the problem becomes oversubscribed, we have proven that it is NP-hard to maximize the total expected priority-weighted sum successful yield of tasks.

We classify scheduling methods into two approaches: on-peak and relaxed. In a *relaxed* approach, tasks can be scheduled at any time an object is trackable. We hypothesize that an algorithm that allows *suboptimal* (with respect to an individual task) scheduling of a subset of tasks can exploit an expectation/utilization trade-off on resource constrained schedules. We develop a simple stochastic local search algorithm that utilizes this arbitration behavior. Paradoxically, this exploitation will result in a *higher overall expectation value* and consequently in a better weighted yield of successful tasks when the schedule is executed.

Our initial work on Spacetrack has focused on two hypotheses. Our first hypothesis is that search algorithms that allow tasks to be assigned execution times with suboptimal expectation values can produce schedules with higher cumulative expectation than could possibly be obtained by placing all feasible tasks on the peak of their signal-to-noise ratios. To test this hypothesis, we show that the on-peak problem can be characterized by a linear integer programming problem in which tractable instances can be solved to optimality using an exact branch-and-bound technique. We next develop a relaxed stochastic local search algorithm that exploits the expectation trade-off. We show that the relaxed stochastic local search algorithm is capable of producing schedules with higher global expectation value than those found by exact branch and bound algorithms.

These results are subject to the following qualification: the degree to which the resource is oversubscribed is critical. Given unlimited resources, all schedules are feasible and a greedy "on-peak" solution will be optimal. However, in any real scenario, the demand for resources is greater that the resource is able to supply. Our results suggest that the more the phased array radar is oversubscribed, the greater the advantage that is obtained by using heuristic off-peak schedulers compared to the exact optimal on-peak. When the resource is heavily oversubscribed the relaxed heuristic methods can allow as much as 25 percent more tasks to be scheduled compared to optimal on-peak methods.

Our second hypothesis is that the advantage of more sophisticated heuristic search methods is cumulative over time. On-peak methods and greedy scheduling methods schedule high priority requests first. Over the course of one day, they may schedule as many or more high priority requests compared to more complex heuristic schedulers. But they do so by ignoring or dropping lower priority requests. However, a low priority request to track a particular bit of space junk can become a high priority request if the object has not been seen in several days. Instead of comparing algorithms by scheduling one day of tasks, we believe it is necessary to take a longer view of how methods compare. Work that is dropped one day just gets pushed into the schedule for the next day, perhaps as a higher priority request. Thus, it becomes important to look at how scheduling methods compare over longer time horizons. Preliminary results suggest that the gap between on-peak and relaxed method performance widens as the longer view is taken. This is still an on-going topic of research.

3 Executive Summary

3.1 Personnel

During the grant period, the following personnel were supported at the indicated level:

PIs:		
Adele Howe	0	months
L. Darrell Whitley	0	months
Research Assistants:		
Mark Roberts	2.25	full-time months (4.5 half-time)
Andrew Sutton	2.25	full-time months (4.5 half-time)

3.2 Publications

Journals

- A. Sutton, 2007 "Exploiting Expectation Trade-off in Probabilistic Modeling with Stochastic Local Search", in preparation.

3.3 Graduate Theses

A Two-Phase Dynamic Local Search Algorithm for Maximizing Expected Success in On-Line Orbit Track Scheduling M.S. Dissertation by Andrew Sutton, Fall 2006. Abstract:

> Until recently, most researchers on scheduling problems assume perfect information is available and that the environment will always behave as predicted. This seldom occurs in practice. Real world scheduling problems contain a large degree of uncertainty, and solutions that anticipate a static environment and perfect information are destined to fail. In this thesis we present a scheduling domain in which radio energy on a phased array radar must be allocated to perform tracking tasks on a set of objects in orbit around the earth. Uncertainty occurs as a function of many factors including target location and orbital behavior. Given past information about an object and its orbital dynamics, we can predict where to focus the radar beam, and how likely a pulse will illuminate it. This information, combined with a priority weighting, gives us the *expected value* of a tracking task: a nonlinear function of schedule decision variables.
>
> Current algorithms typically operate by assigning tasks to start on the peak value of this function: when the probability of success is maximal. If we are maximizing expected success, this is clearly the optimal choice when the resource is not overtaxed. However, when the resource becomes oversubscribed, we show that the general problem of feasibly scheduling tasks on their peak values to maximize expected schedule value is NP-hard and show that it is a bijection to a constrained integer programming problem. When the constraint to place tasks on their peaks is removed, we show the problem becomes hard to approximate. Furthermore, we show empirically that, when this on-peak constraint is relaxed, it is possible to insert more tasks into the schedule. We develop a modified stochastic local search algorithm that exploits this trade-off by influencing its own schedule builder to specify a subset of tasks to be constrained to their peaks. This heuristic algorithm quickly obtains solutions of higher expected value than those produced by on-peak-only methods used in current practice. The gain in expectation corresponds to a higher priority-weighted yield of successful observations.
>
> Our investigation highlights an important result. Oversubscribed scheduling domains exhibiting a trade-off between expected success and resource utilization will benefit from allowing solutions for which a subset of individual tasks have a reduced success probability. Indeed, such a reduction often affords solutions with higher cumulative success.

Andrew Sutton is currently in the Ph.D. program at Colorado State University and is expected to continue working on the Spacetrack project.

Infeasible Search in Oversubscribed Satellite Scheduling M.S. Dissertation by Mark Rogers[2], Fall 2006. Abstract:

> Search algorithms that include both feasible and infeasible solutions have proved to be efficient algorithms for solving some scheduling problems. Researchers conjecture that these algorithms yield two primary benefits: 1) they tend to focus on solutions close to the boundary between feasible and infeasible solutions, where active constraints are likely to yield optimal values, and 2) moves that include infeasible solutions may uncover short-cuts in a search space. Empirical studies have confirmed the value of searching along the feasible-infeasible boundary, but until now there has been little direct evidence that infeasible search yields short-cuts.
>
> We present empirical results in two oversubscribed scheduling domains for which boundary region search in infeasible space appears to offer advantages over search in strictly feasible space. Our results confirm that infeasible search can find short-cuts that may improve search efficiency more than boundary region search alone. However, our results also reveal that inefficient infeasible paths which we call detours may degrade search performance, potentially offsetting efficiency short-cuts may provide.
>
> We explore new approaches that may allow us to exploit shortcuts to improve infeasible search efficiency either by eliminating degrading or unpromising forays or by increasing the opportunities for creating shortcuts in the space. These new approaches yield mixed results for the satellite scheduling domains considered here. However, the algorithms show that by analyzing and exploiting infeasible search behavior we can create highly efficient algorithms.

Mark Rogers is currently in the Ph.D. program at Colorado State University, but has switched his focus to bioinformatics.

3.4 Interactions/Transitions

3.4.1 Presentations at Meetings

M. Rogers for A. Sutton Poster presentation of "Spacetrack: Trading off Quality and Utilization in Oversubscribed Schedules" at *International Conference on Automated Planning and Scheduling*, June 2006 in Lake District, England.

M. Rogers oral presentation of "Looking for Shortcuts: Infeasible Search Analysis for Oversubscribed Scheduling Problems" (co-authored with A.E. Howe and L.D. Whitley) at *International Conference on Automated Planning and Scheduling*, June 2006 in Lake District, England.

D. Whitley "Scheduling Under Uncertainty" talk at annual AFOSR PI meeting

[2]Mark Rogers conducted most of his research under our previous AFOSR contract, but did not defend until shortly after the end of the period.

D. Whitley "Foundations of Genetic Algorithms and Theory: Past, Current and Future" Plenary Talk at the Foundations of Genetic Algorithms 2007 conference, Jan 2007.

3.4.2 Transitions

ITT met members of the team developing the new SPACETRACK system for Eglin AFB. We gave them updates on our analyses and algorithm development for the SPACETRACK application.

A. Data Collected

With the help of ITT and on-line sources, we have constructed two problem sets for SPACETRACK. The first set includes relatively small problems constructed using an automated problem generator and following standard practice in scheduling (e.g., selecting tasks from uniform distributions over fixed values). This set provides experimental control on the amount and type of contention in the schedule; the problems are small enough to be solved to optimality.

The second set includes application consistent problems constructed by selecting objects from a database of 6,000 orbital objects. These four problems were constructed by selecting 2000 or 5000 objects from the database that pass over the radar during a particular 24 hour period. The tasks are configured to follow the distributions of priorities and other attributes actually encountered in real problems.

B. Software

We implemented four scheduling algorithms for Spacetrack; the implementations are in C++ to be run under the Linux operating system. The algorithms are:

On-Peak Local Search which uses local search to select which tasks will be fit into the schedule. All tasks are centered on the peak of the signal-to-noise ratio.

On-Peak Dynamic Local Search which is the same as local search except that it modifies the objective function during search to penalize tasks that have been included in the schedule for many iterations.

Two-Phase Local Search which divides the search into two phases: one which selects the task and the other which determines the strategy for placing the task (on its peak, to the left or to the right of the peak).

Two-Phase Dynamic Local Search which is a dynamic variant of the local search.

We will make our software available on request.

We also have implemented a simulator for the application consistent problems. The simulator divides the day into re-schedule periods, executes the schedule proposed for a particular period, determines which tasks succeeded/failed as a function of their expected probability of success, time slot and resource allocation and updates the task list to include tasks that failed.

The simulator is critical for assessing the value of application consistent solutions and follows the guidelines articulated to us by the developers at ITT.

Web Site Our project web site is available at `http://www.cs.colostate.edu/sched/`. From that site, you can access publications and soon data from the project.